From these considerations the air over desert areas should be considered as warmer, level for level, than air over surrounding areas with a vegetative cover. It would seem that the free air over deserts receives a greater increment of heat in the daytime than it loses by radiation at night and that the excess, small though it may be, is cumulative, so that after a time we should expect that free-air currents from the lower Colorado Valley and the Gulf of California would be warm as compared with currents from the Pacific. The former by reason of the lower specific gravity of the air in them can not flow to the westward. The most likely course of the air is therefore in the direction impelled by the pressure gradient. The latter generally indicates a movement toward the north. The sounding balloons liberated on the six successive days, July 29 to August 3, traveled in a northerly direction and the lowest temperature recorded during the flights was experienced on August 3—the last day of the six in which the free-air currents moved as above stated. When flights were resumed on August 5 the free-air winds were from the SSW. and the minimum temperatures were distinctly higher than during the first-named period, although in some of the flights the balloon did not reach so great a height as in the first period. A better comparison, however, would be to use a definite level reached by all of the balloons furnishing useful records up to, say, 14 kilometers. Such a comparison shows that the temperature in southerly winds was on the average 2.7° lower than in westerly winds. The interpretation of this fact is left in some uncertainty, since the southerly winds of the group July 29 to August 3 had more or less easterly components, which might mean that originally they were of continental origin.

Comparison of the data of Table 1 with the weather maps for corresponding dates leads to some interesting suggestions. The distortion of the isobars in the summer months, before mentioned, makes it difficult to determine the probable direction of the free-air winds from surface isobars, but when the pressure distribution over the entire Rocky Mountain and Plateau region is considered there is better agreement between the pressure gradients and the direction of the free-air winds.

Thus on July 28–29 the west-southwest winds above Santa Catalina Island were evidently due to a cyclonic disturbance that was moving eastward over southern Alberta. This disturbance deepened somewhat and moved east-northeast in the next 24 hours, so that by the morning of the 29th the whole of the northern Rocky Mountain region and the upper Missouri Valley were under its influence. On this date an anticyclone began to pass from the ocean to the land over the States of Washington and Oregon.

On the next day, July 30, this anticyclone had advanced inland as far as northwestern Wyoming and the barometer level at its center had risen to 30.20 inches. Coincidently with this movement the temperature in the free air, as shown in Table 1, rose decidedly; pressure in the free air also rose, but fell slightly at the surface and as a result the isobar inclosing the center of low pressure over Arizona is now projected northward to include the Great Valley of California. In other words, from surface indications one would say that the Arizona and California lows have intensified and merged. But if we take the free-air observations under consideration as an index to what occurred over California and Arizona, it is at once seen that the surface indications are no sure guide to what has actually happened in the free air.

On the next day, July 31, the free-air temperature fell about as much as it had risen the day before. The anticyclone by this time had advanced to western Nebraska; its center now stretched to southeastern Idaho as an oval with central pressure of 30.30 inches, a rather unusual anticyclone for the month of July.

With the entry of this anticyclone over the continent the free-air winds which previously had been southwest now became southerly and as the anticyclone advanced to the eastward the winds became SSE.

It is rather significant that the lowest temperature reached in the whole series of sounding-balloon ascensions was on August 3 at a height of 17,428 meters, and that on the previous day an almost equally low temperature was reached at an elevation of 21,302 meters, thus perhaps indicating a slight lowering of the current of cold equatorial air.

The important thought of the paper, as I see it, is the necessity of a further study of the influence of summer North Pacific anticyclones upon the weather of the Rocky Mountain and Plateau region. It is already known that the movement eastward of these anticyclones gives the clue to shower forecasts for western and central Colorado, New Mexico, Arizona, and southern Utah.[2]

[2] Weather Forecasting in the United States, p. 115.

THE PRESSURE DISTRIBUTION AT VARIOUS LEVELS DURING THE PASSAGE OF A CYCLONE ACROSS THE PLATEAU REGION OF THE UNITED STATES.

By C. LeRoy Meisinger.

[Weather Bureau, Washington, D. C., August 15, 1922.]

INTRODUCTION.

Barometric reductions in the Plateau.—It is important to ascertain what effects, if any, a mountain range, or lofty plateau, exerts on the meteorological elements of a passing storm. The Plateau region of western United States projects into the atmosphere to an average height of approximately a kilometer and a half above the level of the sea over an area of more than 5,000,000 square kilometers. Situated, as it is, in a position of the greatest strategical importance, from the viewpoint of the forecaster, it is essential that he understand very clearly the relations between the surface weather conditions and the pressure distribution.

The problem is a complex of hypsometric effects, and meteorologists are thoroughly cognizant of the fact that reduction to sea level in the Plateau introduces much that is unreal in the horizontal barometric gradients. Owing to the hypothetical nature of the process, the allowance for fallacious effects is a difficult, if not impossible, task, and it is necessary, therefore, to be content with the knowledge of the presence and mode of origin of these false features.

The differences, however, between the probable distribution of pressure at sea level were the continent removed and the actual distribution at the average level of the Plateau where the weather occurs *do* admit of investigation. These differences arise not through faulty reduction methods, but through inherent characteristics of the hypsometric relation. In this way alone the pressure distribution, when reduced to a level from 1 to 2 kilometers below the points of observation, may assume a quite different aspect from that at the average level of the observation points themselves. The magnitude of this difference varies with the intensity of the horizontal temperature gradients.

Bigelow, in devising the system of barometric reductions now employed in the United States, attempted to eliminate this hypsometric effect by assigning such values to the mean temperature of the reduction column as would reproduce on the sea-level map the actual distribution of pressure at about 1 kilometer (actually 3,500 feet).[1] In this he was doubtless partially successful. The weakness of his scheme is the assumption that a given surface temperature is *always* associated with the same mean temperature of the fictitious air column, a view that is incompatible with the evidence obtained by means of kites. While we may grant the partial success of the attempt, the frequent want of conformity of wind speed to indicated gradients affords abundant evidence that it is not always satisfactory.

If, then, the sea-level map in this region represents neither the actual distribution of pressure at the average elevation of the Plateau nor the distribution that would occur at sea level were the Plateau removed, we may justly ask why the attempt to reduce to that level is made at all. This reasoning only leads to the long-recognized truth that, having accurate knowledge of the vertical temperature gradients, we could undoubtedly make a more satisfactory weather map by reducing pressure to some level near that of the station. If temperature arguments are somewhat speculative. there is the compensating fact that the distance through which the reduction must be effected is considerably shortened and the resultant pressure error appreciably reduced.

With the purpose of testing the practicability of making such reductions, and, more especially, of ascertaining in what respects the distribution of barometric pressure differs from one level to another as one ascends from sea level through the Plateau to the free air above, a specific case of the passage of a cyclone across this region has been selected and the corresponding pressure maps drawn for levels 1, 2, and 3 kilometers above sea level.

The cyclone.—The storm in question was that which crossed the United States during the period February 10–16, 1919. Upon the sea-level map, it appeared to enter the United States in the vicinity of Tatoosh Island, Wash., and proceed in a zigzag course across the Plateau in a southeasterly direction, constantly increasing in intensity, until, on the morning of February 13, it was centered at Kansas City, Mo., with the phenomenally low pressure of 978.7 mb. It had assumed an extraordinarily circular form and its diameter much exceeded the latitudinal extent of the United States. High winds prevailed in the Great Plains; dust storms and haze occurred far to the east. The progress of this storm from the Great Plains eastward has already been discussed.[2]

It is now proposed to pursue this storm across the mountainous Plateau. A similar attempt has recently been made by T. Kobayasi[3] in following a cyclone across the low mountains which parallel the east coast of the Korean Peninsula. But his mountain range does not attain the great heights of the Sierras or the Rockies, nor does he have a rugged plateau of vast extent. The presence of water areas within several hundred kilometers east and west of the peninsula would also undoubtedly produce effects markedly different from those of the American Plateau.

Upon the sea-level map, the successive 12-hour positions of lowest pressure were as follows:

February 10, 8 p. m., Tatoosh Island, Wash.
February 11, 8 a. m., Winnemucca, Nev.
February 11, 8 p. m., Yellowstone Park, Wyo.
February 12, 8 a. m., Denver and Pueblo, Colo.
February 12, 8 p. m., Amarillo, Tex.
February 13, 8 a. m., Kansas City, Mo.

From its first appearance until after it passed out of Colorado there was an obvious connection with low pressure farther to the north, beyond the Canadian border. At Winnemucca appeared the first closed isobars, but the number of them increased until, as described above, the circular formation of vast extent overlay the Great Plains and the Mississippi Valley. The evident connection with low pressure outside the field of the maps is significant.

MAPS FOR THE UPPER LEVELS.

Elevations in the Plateau.—While maps have been drawn for three upper levels, they can not, with the partial exception of that for 3 kilometers above sea level, be regarded as free-air pressure maps. There is, to be sure, along the Pacific coast a long strip of land very much closer to sea level than to any of the upper levels. But the Sierras and the Plateau rise abruptly to the east, with the result that most of the stations lie above the 1-kilometer level, and several lie above 2 kilometers. While there are no stations at present operating as high as 3 kilometers, it must not be forgotten that this level is penetrated by mountains at numerous places. In general, the 3-kilometer map represents conditions at the approximate level of the highest points in the Plateau, while the 1 and 2 kilometer levels lie, over considerable areas, below the surface.[4] These maps may be regarded, therefore, as attempts to show what the barometric distribution would have been had the earth been sliced off smoothly at those levels. The following table of stations shows their altitudes and the vertical distances from their barometers to the respective levels. The negative sign indicates that the reduction level lies *below* the station.

[1] Bigelow, Frank H.: Report on the barometry of the United States, Canada, and the West Indies. *Report of the Chief of the Weather Bureau, 1900–1901*, Vol. II, p. 774.

[2] Meisinger, C. LeRoy: The great cyclone of mid-February, 1919. MO. WEATHER REV., October, 1920, 48:582–586.

[3] Kobayasi, T.: On a cyclone which crossed the Korean Peninsula and the variation of its polar front. *Quar. Jour. Royal Met'l. Soc.*, April, 1922, pp. 169–184. Abstract in this REVIEW, p. 356.

[4] While it is not practicable to reproduce a hypsometric map of this region, the interested reader may find a sketch map in the May, 1920, REVIEW, p. 253, which will give an approximate idea of the areas above the several levels.

TABLE 1.—*Elevations of stations in western United States, and the length of reduction columns to the various levels.*

Station	Elevation.		Z_1 meters.	Z_2 meters.	Z_3 meters.
	Feet.	Meters.			
Tatoosh Island, Wash	86	26	974	1,974	2,974
Spokane, Wash	1,929	588	412	1,412	2,412
Seattle, Wash	125	38	962	1,962	2,962
North Head, Wash	211	64	936	1,936	2,936
Portland, Oreg	153	47	953	1,953	2,953
Roseburg, Oreg	510	155	845	1,845	2,845
Eureka, Calif	62	19	981	1,981	2,981
Red Bluff, Calif	332	101	899	1,899	2,899
Sacramento, Calif	69	21	979	1,979	2,979
San Francisco, Calif	155	47	953	1,953	2,953
Fresno, Calif	327	101	899	1,899	2,899
Los Angeles, Calif	338	103	897	1,897	2,897
San Diego, Calif	87	26	974	1,974	2,974
Phoenix, Ariz	1,108	338	662	1,662	2,662
Flagstaff, Ariz	6,908	2,106	−1,106	−106	894
Tonopah, Nev	6,090	1,856	−856	144	1,144
Winnemucca, Nev	4,344	1,324	−324	676	1,676
Boise, Idaho	2,739	835	165	1,165	2,165
Baker City, Oreg	3,471	1,058	−58	942	1,942
Kalispell, Mont	2,973	906	94	1,094	2,094
Helena, Mont	4,110	1,253	−253	747	1,747
Havre, Mont	2,505	764	236	1,236	2,236
Miles City, Mont	2,371	723	277	1,277	2,277
Yellowstone Park, Wyo	6,200	1,890	−890	110	1,110
Sheridan, Wyo	3,790	1,155	−155	845	1,845
Lander, Wyo	5,372	1,637	−637	363	1,363
Pocatello, Idaho	4,477	1,365	−365	635	1,635
Salt Lake City, Utah	4,360	1,329	−329	671	1,671
Modena, Utah	5,479	1,670	−670	330	1,330
Grand Junction, Colo	4,602	1,404	−404	596	1,596
Santa Fe, N. Mex	7,013	2,138	−1,138	−138	862
Roswell, N. Mex	3,566	1,087	−87	913	1,913
El Paso, Tex	3,762	1,147	−147	853	1,853
Abilene, Tex	1,738	530	470	1,470	2,470
Amarillo, Tex	3,676	1,120	−120	880	1,880
Oklahoma City, Okla	1,214	370	630	1,630	2,630
Dodge City, Kans	2,509	765	235	1,235	2,235
Pueblo, Colo	4,685	1,428	−428	572	1,572
Denver, Colo	5,292	1,613	−613	387	1,387
North Platte, Nebr	2,821	860	140	1,140	2,140
Cheyenne, Wyo	6,088	1,855	−855	145	1,145
Rapid City, S. Dak	3,259	993	7	1,007	2,007

Temperature gradients in the Plateau.—There is very little information available concerning temperatures above the surface in the western region, and this greatly complicates any attempt to reduce pressure. Unfortunately, there are no kite stations west of the 100th meridian. Such sounding-balloon ascents as were made off the coast of southern California a few years ago were made in the summertime, and conclusions which one might draw concerning gradients within these lowest 3 kilometers would not be applicable to February conditions. For some years records were kept on the summit of Pikes Peak, Colo. (4,301 meters) and these were subjected by Prof. A. J. Henry[5] to careful comparison with synchronous records at Colorado Springs, Colo. (1,858 meters); similar studies were made of data obtained at Corona, Colo. (3,554 meters), Leadville, Colo. (3,125 meters), and Denver, Colo. (1,613 meters). Valuable as these data are, it must be true, from what we know of kite data, that vertical gradients of temperature based upon measurements at two points separated by considerable vertical distance, both of which are surface stations, can not properly account for the sinuosities of the intervening lapse rate. Nevertheless, these mountain gradients afford the only thread of direct observation we have.

There is the line of aerological stations, consisting of Ellendale, N. Dak., Drexel, Nebr., Broken Arrow, Okla., and Groesbeck, Tex., from which considerable information is to be obtained regarding vertical gradients, but these stations are at a much lower level, and their results must be applied to mountain stations with discrimination.

The values given by Professor Henry, expressed in degrees centigrade, per 100 meters, for the gradient at Colorado Springs, are as follows:

[105th Meridian time.

5 a. m	0.44
6 a. m	0.45
5 p. m	0.70
6 p. m	0.65

The 5 o'clock values are applicable to the observations taken in 120th meridian time.

For the kite stations, when the diurnal variation is not considered, the values are smaller than those given above, showing a tendency toward strong inversions in February at Ellendale, lesser inversions at Drexel, and small positive lapse rates at the two southern stations.[6] The kite records have the advantage of being integrated over small altitude divisions, whereas the mountain data are based on two points only.

Therefore, in cases where the air columns were quite long, and the latitude southerly, it was believed that, for morning observations, a gradient of 0.5° C. per 100 meters might reasonably be employed; that in middle latitudes 0.3° C. or 0.4° C. per 100 meters; and that in the north of the Plateau 0.2° C. per 100 meters. For short air columns a small positive or possibly a small negative lapse rate might account closely enough for the vertical temperature distribution. In the evening the lapse rate employed was, in all cases, higher.

Temperature gradients on the Pacific coast.—On the Pacific coast (which offers a different problem from that of the Plateau) at the time of this cyclone the station on Mount Tamalpais, near San Francisco, was maintained. Its altitude was only 724 meters above sea level and it could serve only in the most general way as an index to the mean temperature over San Francisco up to 1 kilometer above the sea. The vertical gradient between San Francisco and Mount Tamalpais at the time of the observations in question was about 0.7° C. per 100 meters, there being little difference between morning and evening observations. This indicated that along the Pacific coast a larger lapse rate should be used than that employed for interior stations.

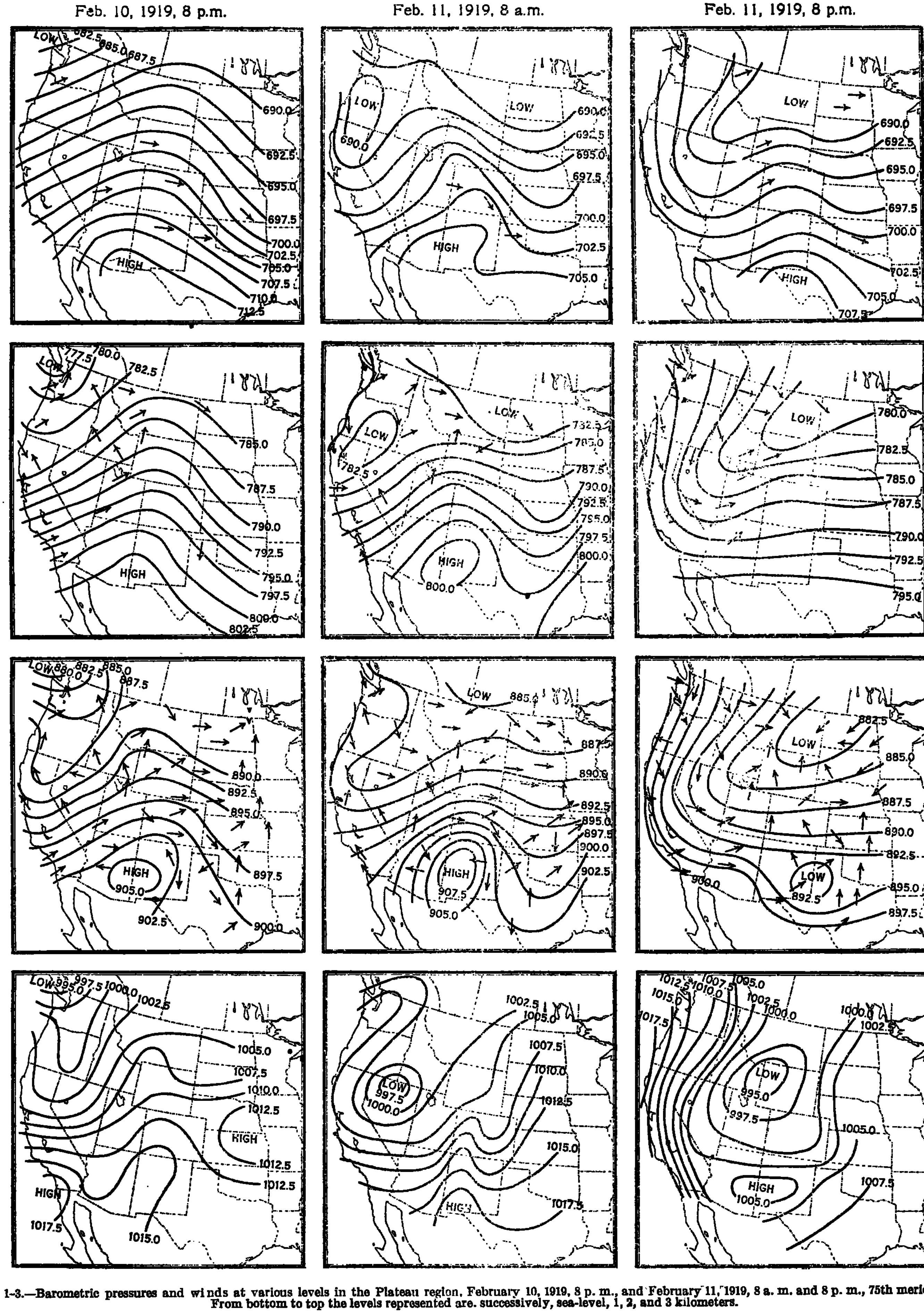
Reliability of the maps.—These are the only bits of direct evidence one has for determining the probable mean temperature of the air column. Since they are probably quite close approximations, and since the length of the air column was, in most cases, very short, it is believed that the computed pressures are approximately correct. This is especially true for the 1 and 2 kilometer maps. Within air columns 1 kilometer in length, errors of 5° C. (certainly the error in this study is not of that magnitude) result in pressure errors of about 2 mb. Therefore, we may have considerable confidence in the results obtained, even though the maps must be regarded as only approximate. It may be added that Kobayasi[7] used the gradient of 6° C. per 1,000 meters throughout his study, and yet he placed considerable weight on the appearance of secondary depressions upon his maps.

Method of computing pressure for 3 kilometers above sea level.—The pressures for 1 and 2 kilometers above sea level were calculated directly by means of the hypsometric formula. The pressures for the 3-kilometer map were computed somewhat differently, and may be, as a

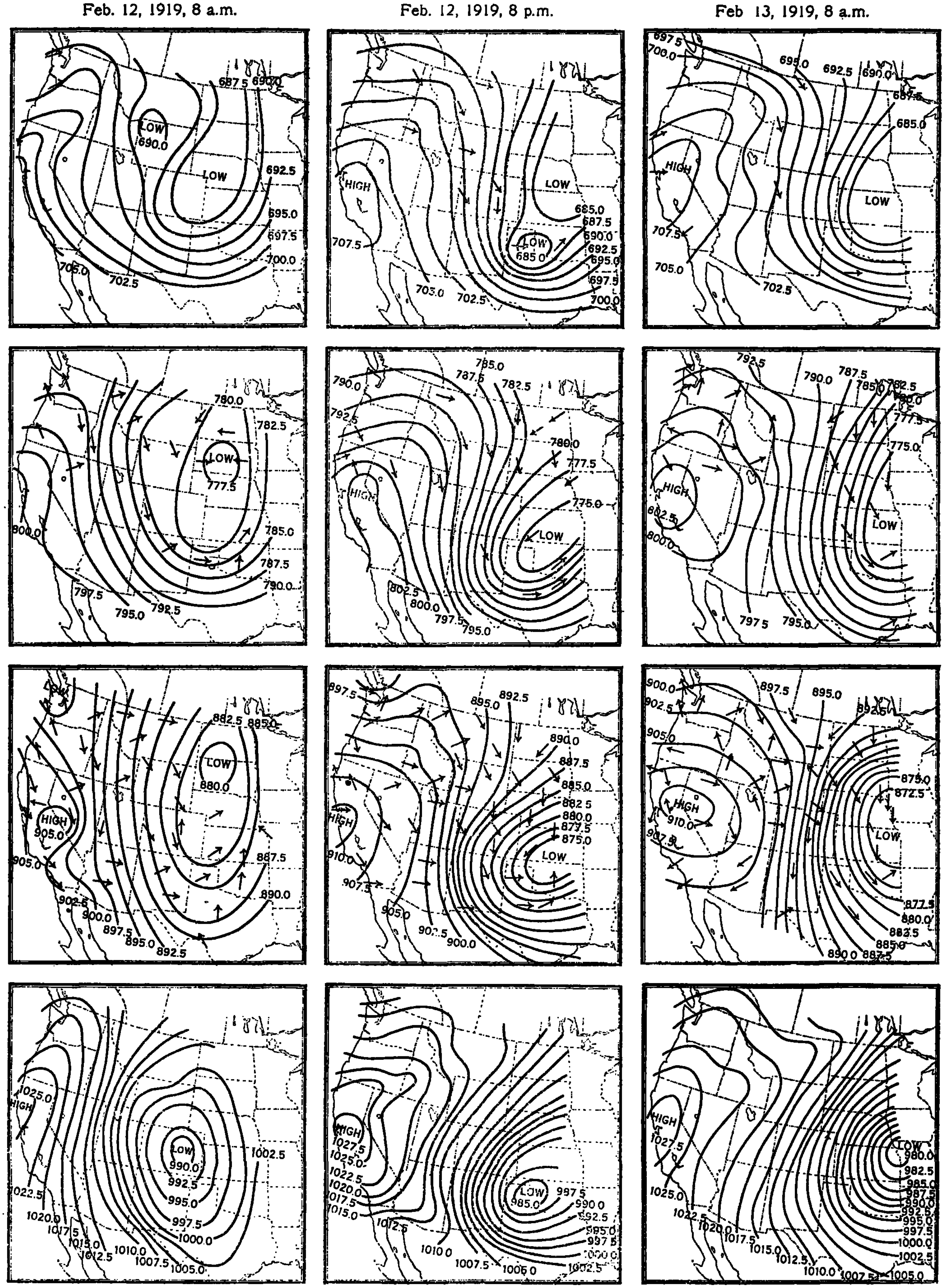
[5] Henry, A. J.: Variations of temperature and pressure at summit and base stations in the Rocky Mountain region. *Bulletin of the Mount Weather Observatory*, Vol. III, part 4, 1910, pp. 201-225.

[6] Gregg, W. R.: An aerological survey of the United States. Part I. Results of observations by means of kites. MO. WEATHER REV. SUPPLEMENT No. 20.

[7] Loc. cit.



FIGS. 1-3.—Barometric pressures and winds at various levels in the Plateau region, February 10, 1919, 8 p. m., and February 11, 1919, 8 a. m. and 8 p. m., 75th meridian time. From bottom to top the levels represented are, successively, sea-level, 1, 2, and 3 kilometers.



FIGS. 1–6.—Barometric pressure and winds at various levels in the Plateau region, February 12, 1919, 8 a. m. and 8 p. m., and February 13, 1919, 8 a. m., 75th meridian time. From bottom to top the levels represented are, successively, sea-level, 1, 2, and 3 kilometers.

consequence, *less accurate than the other two maps.* But it is thought that it is more accurate than a computation based upon an assumed temperature for so long an air column.

It was found that the difference between the average pressure at 1 kilometer and that at 2 kilometers above sea level in February is practically the same at each of the four kite stations mentioned above. In a like manner, there is little difference among the several stations regarding the difference of average pressure between 2 and 3 kilometers above sea level. We may therefore form a proportion between the average pressure differences and the current pressure differences. Thus,

$$D_{1-2}/D_{2-3}=d_{1-2}/d_{2-3}$$

and

$$d_{2-3}=d_{1-2}D_{2-3}/D_{1-2},$$

in which D_{1-2} and D_{2-3} are the differences between the average February pressures at the levels indicated by the subscripts; d_{1-2} and d_{2-3} are corresponding current differences at Plateau stations, the former being derived from calculation and the latter being unknown. Upon the basis of the kite data,[8] the ratio D_{2-3}/D_{1-2} was found to be 0.89, whence,

$$d_{2-3}=0.89\ d_{1-2}$$

It should be stated further that in cases in which observations were made at the four kite stations those observations have been plotted and used on the maps for the eastward extension of the isobars.

Having plotted the various pressure values figures 1 to 6 were obtained, which show for sea level and each of the three upper levels the pressure distribution for each 12 hours between February 10, 8 p. m., and February 13, 8 a. m., 75th meridian time. In these figures the lowest row of maps represents sea level conditions, the successive rows above represent the pressure distribution at successive altitude intervals of one kilometer.

The effect of diurnal temperature variation.—A further word is necessary concerning the comparison of sea-level maps with those for the upper levels. In addition to the temperature argument already introduced into the tables by Bigelow, there is the procedure of averaging the current and the preceding 12-hour surface temperature to be taken into account. This is regularly done at Weather Bureau stations, and it tends to smooth out and prevent strong diurnal changes in intensity of pressure at the low level, the purpose being to make the morning and evening maps comparable. In drawing the upper charts this average temperature was not used, and for two reasons: (1) So far as possible, it was desired to show the pressure actually existing; and (2) it was found, upon examining the diurnal changes of temperature during this period at numerous stations that the effect of this daily swing would hardly be perceptible upon the upper maps. Such a variation would tend to make the pressure lower at low levels with high temperature than with low temperature; at high levels the reverse would be true. The effect would be most marked, of course, in regions having a large diurnal variation. Whatever slight discrepancy in comparability there may be between sea level and the upper maps does not interfere to any significant extent with the horizontal gradients.

[8] Aerological Survey of the United States, *loc. cit.*

THE CYCLONE AT UPPER LEVELS.

The 3-kilometer maps.—With the general sketch of the sea-level performance of this cyclone as a background, let us first examine the 3-kilometer charts for the period. Upon these charts have been drawn the directions of *upper* clouds as reported telegraphically. These clouds probably lay far above the 3-kilometer level and their direction of movement presumably indicated the approximate trend of the isobars at still higher levels. Owing to the short time allotted the observer for the taking of his observation, the direction of upper clouds is not always perfectly reliable. With a few exceptions, however, it will be seen that the reported direction of upper clouds either conforms to the isobaric trend at 3 kilometers or shows a trend somewhat more from the west.

Beginning with the first of the series at 3 kilometers, the conventional conception of the free-air isobaric trend is well exemplified. There is high pressure over the Southern Plateau and low pressure to the north; the isobars are evenly spaced. From a point in the Northern Plateau there is lower pressure both to the east and the west. As we advance through the period, the evidences of low pressure at this high level are all very closely related to the general low pressure in the north and the isobars in the main are open to the north. Toward the end of the period the low pressure in the free air pushes farther south over the Great Plains, but the isobars are oval in form and tend to open to the north.

High pressure in the south and low pressure in the north in the free air are the obvious consequences of high temperature in the south and low temperature in the north. This horizontal gradient of temperature is most accentuated in winter, but is by no means extreme in these maps. The decided southern looping of the isobars immediately after the Plateau is crossed suggests at once the connection between topography and the distribution of pressure.

The 1-kilometer and 2-kilometer maps.—Upon the 2-kilometer map have been drawn arrows corresponding to the reported direction of *lower* clouds. In general, the agreement is good, but, though the accuracy of observation is greater, the topographic influence upon wind direction is more strongly operative, so that as one approaches the surface in this mountainous region more and more frequent will be the discrepancies between isobaric trend and recorded wind direction.

The 2-kilometer and the 1-kilometer series act in practically uniform manner as intermediaries between the distribution at 3 kilometers and at sea level. As one proceeds downward from 3 kilometers the pressure change for a given station from one day to the next becomes more and more intense, and in all cases there is a significant increase in the horizontal gradients just as soon as the formation gets across the Plateau.

There is the outstanding feature, however, that the sea-level map *does not* coincide with the 1-kilometer map, showing that, at least in this case, Bigelow's attempt was not perfectly successful and that *the pressure at the general level at which the weather occurred was not characterized by the steep gradients shown on the sea-level map.*

For example, winds at no time were excessively high on the Plateau, in spite of the indicated intensity of the gradients. The only high winds associated with the storm occurred as it passed into the Plains States, when the dust storms mentioned earlier occurred. At the time of the last map, when the gradient was only slightly steeper at North Platte (about 1 kilometer) than at Cheyenne (about 2 kilometers) there was a difference of wind speed of about 10 meters per second, the North Platte wind being the higher. When the storm was apparently centered in Colorado, 24 hours earlier, neither Pueblo, Denver, Grand Junction, Salt Lake City, nor Cheyenne reported wind velocities in excess of 5.3 meters per second. The following brief table of pressure differences between Denver and Salt Lake City on this date (morning of February 12) shows how the gradient decreased with altitude:

TABLE 2.—*Difference in pressure between Denver and Salt Lake City at various levels, 8 a. m. (75th meridian time), February 12, 1919.*

Level.	Pressure difference *mb.*	db/dB.
Sea level	11.5	1.00
1 kilometer	10.0	0.87
2 kilometers	7.0	0.61
3 kilometers	7.0	0.61

The ratio db/dB is that between the pressure difference at the level in question and at sea level; in other words, it is the percentage of sea-level difference observed at the upper levels. From this it is clear why the wind indicated by the sea-level gradients did not occur.

The classification of the storm.—According to the classification given in *Weather Forecasting in the United States,*[9] this storm was of the North Pacific type, which reaches its maximum intensity in February, as a rule. The path taken on the sea-level map was not unusual, but, says the manual:[10]

> By reason of topographic conditions, the movement of North Pacific LOWS across the Plateau and Rocky Mountain region is often masked and difficult to follow; in some cases it is almost impossible to locate the true center of the disturbance on the synoptic charts.

The synoptic charts mentioned are, of course, the sea-level charts.

Allobaric charts and their significance.—Allobaric charts are always of interest, because of their value to the forecaster in predicting the movement of pressure centers. A series of these maps has been drawn for sea level and also for 3 kilometers. These two levels will suffice, since changes at intermediate elevations were intermediate in magnitude. It will be seen that the pressure changes are, in general, in the same direction but of smaller magnitude at the upper level. The first sea-level map in Figure 7 shows two katallobaric centers of equal intensity, the one southeast, the other northeast, of Winnemucca, the center of lowest sea-level pressure on the morning of February 11. Since the allobaric charts have their chief significance as indicators of the probable movement of the center of lowest pressure, there might be some doubt, leaving other factors out of consideration, as to whether the storm would continue to move toward the southeast (the direction of its motion during the previous 12 hours) or whether it would move toward the northeast.

As a matter of fact, the center did move to the northeast and appeared, on the sea-level map, near Yellowstone Park. The 3-kilometer katallobars would have been equally deceiving, since at that level the pressure fell most markedly over the southern Plateau, an effect which may be attributed in small part to the diurnal fall of temperature. However, the distribution of pressure at 3 kilometers (fig. 3) would have settled the question beyond doubt, since the presence of the primary cyclone in the north is definitely shown.

Figure 8 shows the distribution in time of pressure changes at sea-level and at 3 kilometers at Santa Fe, N. Mex.

Precipitation.—The precipitation over the Plateau was principally in the form of rain, although snow fell during the latter part of the period in the Rocky Mountains. The rains, which occurred generally along the Pacific coast and some distance inland, can be shown by the upper maps to follow quite directly from the importation of moist air from the Pacific as a result of the circulation about the cyclone in the north.

Temperature.—The distribution of temperature is of fundamental importance, especially when one considers the increase in intensity of the depression after it entered the Plains States. While the storm was on the Plateau there was no exceptionally marked latitudinal gradient of temperature. As the storm approached the Plains, however, and the southerly winds began to draw upon that great reservoir of warm, moist, air over the Gulf, the rapid northward migration of the surface isotherms began. Within the period represented by the last three maps, the temperature difference between the northern and southern borders of the United States along the 95th meridian increased from about 11° C. to 28° C., and the isotherm of 10° C. was shifted markedly northward in the Mississippi Valley. Similarly, in the rear of the storm, low temperatures were induced in the northern Plains. The result was to accentuate the thermal contrast between the front and rear of the storm. This would emphasize the southwest winds at upper levels and thus cause—if we may have confidence in the precept that cyclones move in general with the upper drift—an accelerated movement of the cyclone toward the northeast. This suggestion is rendered plausible by the fact that 48 hours after the storm was centered at Kansas City the center of lowest pressure was passing off the coast of New England.

This thermal contrast would likewise have the effect of opening the free-air isobars to the north and causing the axis of the cyclone to incline toward the region of lowest temperature. From this point of view, the center in the free air probably traced a track somewhat parallel to that at sea level but approximately along the northern border of the United States. All available upper-air soundings in central and eastern United States support these conclusions.[11]

HYPSOMETRIC EFFECTS IN THE PLATEAU.

What does the sea-level map in the Plateau represent?—In the beginning, it was remarked that since we can not precisely evaluate the error in Plateau reductions which arises through an erroneous temperature argument, it is convenient, so far as this study is concerned, to consider the sea-level map as a correct representation of what might be found there were the continent removed. This is not what Bigelow intended, but we know from the difference between the sea-level and 1-kilometer charts that what he intended was not, in this case, achieved. We may conclude that the sea-level map is a smoothed or softened representation of the distribution at sea level were the continent removed. In other words, a true sea-level map would probably show even

[9] Weather Bureau No. 583, Washington, 1916.
[10] *Op. cit.*, p. 120.
[11] Meisinger, C. LeRoy: *loc. cit.*

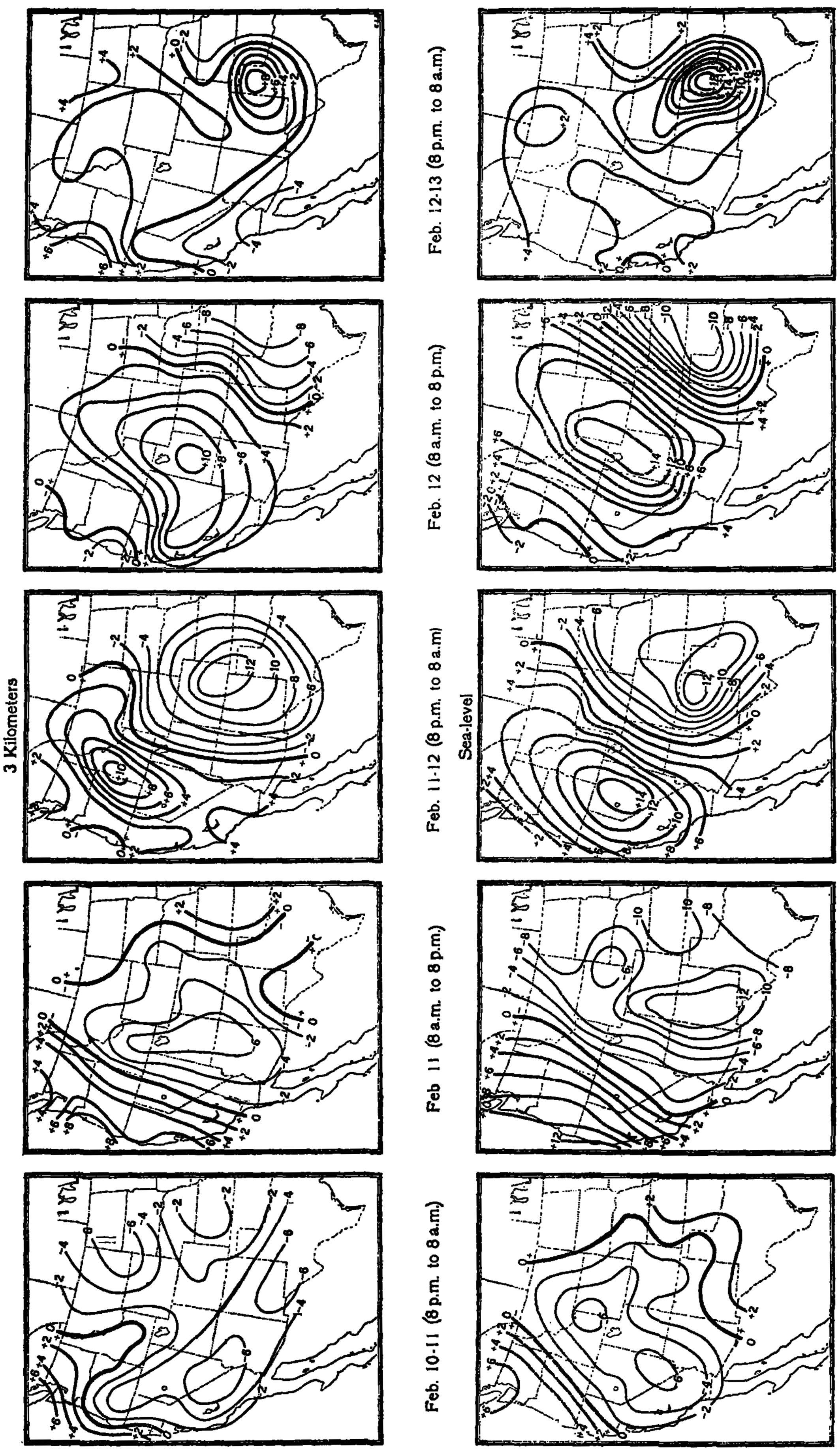


FIG. 7.—Pressure changes for 12-hour periods at 3 kilometers above sea level and at sea level.

steeper horizontal gradients than the present one, reduction errors neglected.

The hypsometric formula.—To make this thought clearer, let us recall certain consequences of the hypsometric relation which must make their effect apparent at different levels. In exponential form, this relation is

$$B = b\ e^{\frac{Z}{K(1+\alpha\theta)}}$$

in which B is the pressure at a lower level, b the pressure at an upper level, K the barometric constant, 7991, Z the length of the reduction column, α the coefficient of gas expansion and θ the virtual mean temperature of the air column. If this equation is differentiated, we have,

$$dB = db\ e^{\frac{Z}{K(1+\alpha\theta)}}.$$

From this it is apparent that, for a given gradient of pressure at an upper level, the gradient at a lower level will be somewhat greater, depending upon the distance between the two levels and the temperature. Specifically, if db is 10 mb., Z, 3,000 meters, and θ, 0° C., we find that dB is 14.5 mb.

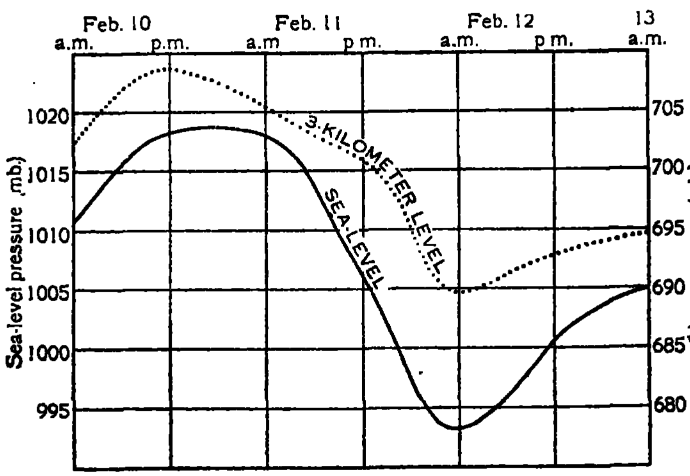


FIG. 8.—Pressure changes at sea level and 3 kilometers above sea level at Santa Fe, N. Mex.

This assumes no difference in the mean temperature of the air column. But if there is a difference of 5° C.,—and since higher temperature is usually associated with falling pressure—we assume the higher temperature at the station of lower pressure, and find that dB is increased to 22.1 mb., over twice the gradient at the upper level. Exner has shown [12] how pressure differences at the surface are a complex of pressure and temperature effects as shown by sounding-balloon data and by partial differentials of free-air pressure and mean temperature of the air column.

The essential point is that gradients of considerable magnitude may appear at sea level corresponding to lesser gradients at the Plateau level. But there is no atmospheric circulation to correspond to the sea-level gradients because there is no atmosphere at that level.

Since we may consider the barometric depression as superposed upon the northward-sloping, temperature-induced, isobaric surfaces, it is apparent that the center of lowest pressure will be shifted northward at each succeeding upper level. The maps here presented confirm this reasoning, and we find upon the sea-level map a system of stronger gradients with closed isobars lying south of the center of lowest pressure at upper levels.

PLAINS AND PLATEAU EFFECTS COMPARED.

What happens when the storm passes off the Plateau into the Great Plains? We have already noted the general increase in activity and intensity in the latter part of the period and there are several effects to be taken into consideration in this regard. Supposing, first of all, that there were no increase in the intensity of the storm; what differences might arise between Plateau weather and Plains weather?

(1) As the storm moves eastward, the more active gradients at lower levels become real. There results a natural increase in the speed of the winds, and the circulation at the surface corresponds more closely to that indicated by the sea-level map.

(2) Surface friction over the level plains is much smaller than that over the rugged mountains, hence higher wind velocities are to be expected. There is the effect of greater density at lower levels than at the Plateau level which would tend to counteract this increase to a certain extent.

(3) With warm, moist air to draw upon in its southeastern quadrant, the thermal contrast between front and rear of the cyclone would be increased. This would cause a shift of the center of low pressure in the free air to the region of lowest temperature, and induce a general lowering in elevation of the southwesterly air stream aloft. Warm, moist air would thus overrun the sea-level center of lowest pressure.

Increase in intensity.—Not only did the storm show all the effects mentioned above, but it showed a marked increase in intensity which reached a climax at Kansas City and then gradually decreased with further eastward movement. This increase in intensity may be the result of the following effects:

(1) It was suggested that reduced sea-level gradients in the Plateau were not as strong as they might have been had Bigelow not attempted to make sea level show surface conditions. In the Plains States the stations are close enough to sea level that no great errors result in reduction thereto. Hence a given gradient in the free air should correspond to a steeper gradient in the Plains States than in the Plateau. This may account in part for the apparent increase in intensity after leaving the Plateau.

(2) Considered statically, the increase in temperature above the sea-level center of the storm combined with the lesser density of the moist air and reinforced, perhaps, by the retarded lapse rate of temperature (for precipitation was general by the morning of the 13th over the Southern States and central valleys) would operate to lower the sea-level pressure. The warm and cold fronts were, at this time, well developed, and this implies an upward component in the motion of the southerly air, both because of the forced convection of warm air overriding the cold air north of the warm front, and also because of convergence within the southerly stream itself.

(3) Whatever the nature of the dynamic effects which may have operated to increase the storm's intensity as it proceeded from the Plateau to the Plains, it appears that the interaction of the southwestward-moving cold-

[12] Exner, F. M.: *Dynamische Meteorologie.* Berlin, 1917, pp. 233–238. Cf. also discussion in *Ibid.: Über Luftdruckschwankungen in der Höhe und am Erdboden*, Meteorologische Zeitschrift, September, 1913, pp. 429–436; also November, 1913, pp. 563–564.

air stream to the north and the northeastward-moving warm stream to the south of the center was an important factor. J. Bjerknes and H. Solberg [13] have recently emphasized this point. On page 15 of the work cited they say:

> At the limit between a polar current and a tropical current to the east of it the two currents are deflected from each other, so that an air deficit results above the region of their mutual limit. The low-pressure system, formed in that way, corresponds to a cyclone family.

And, again, on the following page:

> As soon as an easterly polar current and a westerly tropical current become too strong a cyclone forms between them and makes the currents encroach upon each other, diminishing their differences of velocity.

CONCLUSION.

It seems reasonable to conclude, therefore, that maps representative of conditions at and above the average level of stations in the Plateau would be of assistance to the forecaster in distinguishing between those barometric gradients on the sea-level map which are real and those which are either erroneous or follow as a consequence of the hypsometric relation. Further, the change in the character of the weather after the storm passed from the Plateau to the Great Plains is plainly due to (1) the effect of stronger gradients near sea level becoming real through having an actual atmosphere in which to exist; (2) the sea-level gradients becoming stronger upon leaving the mountain district because of moderating effects in the reduction method; and (3) actual increase in intensity of the storm.

[13] Bjerknes, J., and Solberg, H.: Life cycle of cyclones and the polar front theory of atmospheric circulation. *Geofysiske Publikationer*, Vol. III, No. 1. Christiania, 1922.

A CYCLONE WHICH CROSSED THE KOREAN PENINSULA

By T. KOBAYASI.

[Abstracted from *Quar. Jour. Roy. Met'l Soc.*, April, 1922, pp. 169-184.]

With the twofold object of studying the phenomena induced by the passage of a cyclone directly across a mountain range, and of noting the behavior of the polar front in the Far East, the author makes a series of maps representing pressure distribution at sea level, at intervals of four hours between 10 a. m. March 24, and 2 a. m. March 26, 1918. Upon the assumption of a lapse rate of 6° C. per 1,000 meters for all stations, pressure maps at 3 kilometers above sea level are drawn to correspond to 6 of the sea-level maps.

At the time when the cyclone was 500 kilometers west of the Korean Peninsula, which "projects from the southeast coast of the Asiatic Continent in the direction of south-southeast, the width being from 200 to 300 kilometers, the length about 600 kilometers," and which contains a mountain range from 500 to 1,000 meters in height along its eastern coast, a secondary cyclone was induced on the eastern side of the peninsula, but it disappeared within four hours. But by the time the cyclone had advanced 100 kilometers, a second secondary, with a well-developed polar front, had appeared. The formation of these secondaries, according to the author, is due to the strong wind of the primary storm being obstructed by the mountains.[1]

The free-air maps show that these secondaries did not extend much above 3 kilometers and their axes are so inclined as to "wind themselves around the main cyclone."

A third secondary, associated with a sharp bend in the steering line, formed to the northeast of the main center. The free-air maps show the centers of the primary and the last two secondaries drawing gradually together, as if they were joined together at some higher level. The eastern secondary continually increased in intensity, while the primary diminished; the northern secondary finally joined with the eastern center, and finally the western center disappeared entirely. Thus, the cyclone crossed the peninsula.

Considering the cyclone from the Bjerknesian point of view, the behavior of the storm was quite normal, except as it was influenced by topography. Dr. S. Fujiwhara's new theory of the mechanism of extratropical cyclones (as yet unpublished) requires the presence of a horizontal vortex roll along the "cold front" having a counterclockwise sense of rotation facing the center, and of a similar vortex roll on the "warm front" of opposite sense of rotation, "and this vorticity makes the principal source of energy for the cyclone." The intersection of these warm and cold fronts with mountain ranges, induces secondaries, and produces anomalous wind directions. The phenomena shown in the Korean cyclone seem to confirm Doctor Fujiwhara's theory.

The following is the author's summary of the causes of secondaries:

> (1) When a strong wind was obstructed by mountains, a secondary *was induced kinematically in the shadow.* (This kind of secondary vanishes soon if it does not connect with the polar front.) (2) When the steering line was cut by a mountain range, a secondary was induced on the eastern side of the range. (3) When the steering line curved sharply. (4) When the real polar air came after the cyclone had passed away, a secondary was produced in the cold sector, prolonging the steering line of the main cyclone to the west of its center. (5) Along the squall line when the fault of the isobars became very large.

The paper is concluded by miscellaneous remarks concerning the storm: the inclination of the axis of the cyclone is less over the sea than over the land. In the latter case, the lower part of the cyclone is nearer the sea than the upper portion.[2] This cyclone acts in accordance with Prof. T. Terada's conclusions from a statistical study of cyclones in the Far East, namely, that cyclones tend to pass over land in summer and tend to avoid land in winter.—*C. L. M.*

[1] Cf. Brooks, C. F.: On the origin of some secondary cyclones on the Middle Atlantic Coast. Mo. WEATHER REV., January, 1921, 49: 12-13.

[2] Preliminary studies of cyclones in the eastern United States show this same tendency, which is explained by strong contrasts of temperature between the southeast and northwest quadrants of the storm. *In summer, the axis is more nearly vertical as was found* to be the case over the sea, in Doctor Kobayasi's cyclone, probably due to the less-marked horizontal temperature contrast in the lowest 3 kilometers.—*C. L. M.*